EXPLORING THE SOLAR SYSTEM

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"Astronomy compels the soul to look upwards and leads us from this world to another." Plato (427? – 347 BC): The Republic

Almost 400 years ago in 1610, Galileo used a telescope to look upwards into the starry sky and changed the view of the solar system forever. Faint points of light became planets with distinct features and orbiting moons. Other planets, Uranus, Neptune and Pluto, were discovered with the aid of this new instrument and as the technology improved so did our window into these strange new worlds become clearer.

It was not until 1962 when the first planetary spacecraft Mariner 2 flew by Venus that the next revolution in planetary exploration occurred. Robotic explorers have visited every planet in our solar system except Pluto. With each new voyage our understanding of the creation and evolution of the solar system was transformed and the uniqueness of our own planet Earth was reinforced. Planetary systems of unanticipated diversity continuously challenged our perceptions and beckoned us to continue the exploration with evermore complex spacecraft.

As diverse and unique as these worlds are in detail there exist properties that are common among them. It is this commonality that will help us understand the origin and evolution of our solar system and the origin of life on Earth and perhaps elsewhere. This fundamental knowledge serves as the basis for extending our understanding beyond the confines of this solar system to other planetary systems in the universe.

Five of the most common properties that have been discovered and will be discussed through examples are as follows:

- Tectonics: the geological activity that creates mountains, earthquakes, volcanoes, and that causes continents to drift about the surface of Earth
- Collisions: impacts by foreign objects causing cratering of surfaces and effecting the evolution of many bodies
- Organics: materials such as hydrocarbons that contain carbon

— Weather systems: atmospheric conditions that may contribute to environmental changes
— Liquid water: essential property for the creation and evolution of life

Tectonics

On Earth, mountain ranges are well-known features and the existence of earthquakes and volcanoes are all too familiar in many regions. The internal geophysical activity at the core of our planet is driven by the slow decay of radioactive material. This heat source causes the movement and collision of continental plates resulting in the formation of mountain belts, earthquake faults and volcanic activity.

Known to ancient astronomers, Venus is Earth's sister planet because it is similar in size and density and orbits the Sun at a comparable distance. Although the planet is surrounded by opaque sulfuric acid clouds and a thick atmosphere of carbon dioxide, radar images from the Magellan spacecraft have unveiled a surface scattered with mountain ranges, volcanoes and fault systems. The similarities between the two planets is however limited.

The surface of Venus is relatively young, perhaps about 800 million years old. Since Venus formed at the same time as Earth about 4.6 billion years ago, some event or events must have resurfaced the planet. The evidence indicates that massive outpourings of lava from the planet-wide volcanic eruptions may have been the cause. Two large volcanoes, Sif Mons in the background and Gula in the foreground (Fig. 1) are examples of such features. Although Venus may still have active volcanoes, no visible outpourings of lava were detected during the mission.

The distribution of volcanoes around Venus is also of interest. On Earth, volcanoes occur in groups such as the "Ring of Fire" around the Pacific Rim. By contrast Venus has hundreds of thousands perhaps millions of volcanoes distributed randomly around the planet. Lava channels thousands of kilometers long were also a surprising discovery.

Despite the large volcanic activity, there appears to be no continental plate tectonics about the surface of Venus as there is on Earth. This suggests that the interior of the planet is different than Earth in major ways. In particular Venus seems to lack a buffer layer that exists within Earth between the outer part of the planet and the mantle beneath. As a result, the gravity signature of features on Venus closely reflect surface topography, whereas on Earth such a correspondence does not always occur.

Bodies in the outer solar system are expected to be geologically dormant because the temperatures are very much colder. Io, one of the four Galilean moons orbiting Jupiter, has the greatest tidal heating in our solar system today. The small moon (Fig. 2) has eight active volcanoes and more than a hundred hot spots — active volcanic areas glowing with lava flows, a hundred times more than here on Earth. No impact craters can be seen on the surface of Io because they have all been covered by the continuing volcanic activity. There are large black features thought to be lakes of liquid sulphur. Io is in effect turning itself inside out, erasing all record of any impact craters, and continuing today to renew its surface at a very high rate. The tidal flexing causes the solid surface crust to flex up and down about 100 meters. Comparable tidal effects on Earth raise the ocean water levels by 18 meters.

Tectonic activities driven by a variety of sources of heat are common among many other bodies in our solar system and like the Earth have helped shape the evolution of these bodies.

Collisions

Impact craters such as we see on our moon and many other planetary bodies are the result of collisions. Throughout the solar system we find that collisions are not just cosmetic but have had a critical role in the geophysical evolution of planets and moons.

The entire ring system of Saturn is likely the result of a break-up of one or more larger bodies that were in orbit around the planet. Saturn's rings (Fig. 3) are made up of many small particles a few centimeters in size, fewer larger ones, and fewer still of the largest ones some meters across, as is expected from a collisional process.

Although much of the cratering record on Earth has been erased, impacts have been important. There is evidence that a large impact 65 million years ago may have created an abrupt change in Earth's environment, causing the extinction of dinosaurs and many other species. Collisions likely altered not only the geological evolution of Earth, but affected life itself.

Our own Moon resulted from the impact of a Mars-sized object colliding with Earth. This object impacted early in the formation of Earth melting the outer portion of our planet and splashed material into orbit where it slowly condensed into the Moon.

Collision processes are still active today. In 1994, Comet Shoemaker-Levy captured by the strong gravitational forces of Jupiter slammed into the planet (Fig. 4). This is the first collision of two solar system bodies ever to be observed. The comet consisted of at least 21 observable fragments with diameters estimated at up to 2 kilometers.

We now know that collisions occur the throughout the solar system and are not just minor cosmetic impacts as we first expected. They can greatly affect the evolution of a body itself and more importantly the evolution of life.

Organic Materials

Organic molecules that are abundant on Earth are due to the presence of life but life is not necessary for the presence of organic materials. How do pre-biotic molecules originate? On Earth we have an atmosphere and an ocean that allows complex chemical processes to synthesize organic material but these processes can also be found throughout the solar system.

Comets are covered with a charcoal black surface and emit a fine dust that was discovered to be organic material. This suggests that the dark crust of a comet is also made up of organic material. Many of the icy moons in the colder regions of the solar system have similar dark material that likely contains carbon of organic origin.

The synthesis of organics is even more abundant on Saturn's moon Titan. As large as the planet Mercury, Titan has an atmosphere of mainly nitrogen, like Earth, but lacks the oxygen produced by living organisms. Instead, Titan is surrounded by methane, natural gas, that is converted by the Sun into hydrocarbons forming an opaque haze (Fig. 5). The Hubble Space Telescope was able to peer through the haze using infrared rather than visible light imaging the surface and discriminating between lighter and darker regions (Fig. 6). Some of the organic material in the atmosphere should be liquid and precipitate or rain onto the surface forming dark lakes of liquid hydrocarbons.

At a temperature of –180° C, the surface of Titan is too cold for the complex chemistry that led to life on Earth. Titan does serve as a natural laboratory and a new source of organic material whose origin and composition we do not understand. The chemistry occurring there now may provide important clues to the chemistry that occurred in early Earth's atmosphere before life evolved.

Weather Systems:

The outer giant planets starting with Jupiter are like the Sun, fluid gaseous spheres with no solid surface. Jupiter's clouds are ammonia ice crystals with deeper clouds made up of water ice. Emitting about twice as much heat as it absorbs from the Sun, the planet has a dynamic weather system. Dozens of large, circular storms are generated by turbulent flow associated with jet streams of more than 300 kilometers per hour. The Great Red Spot (Fig. 7) is a hurricane more than three Earth diameters across. This spot was detected by Galileo and has not subsided in at least 400 years.

The planet Neptune is six times further from the Sun and with only 5% as much energy to drive winds as there is on Jupiter. It appears as a bright blue globe from the methane in the atmosphere and has jet streams of more than 2,000 kilometers per hour, the highest observed in the solar system. A Great Dark Spot (Fig. 8) consisting of methane ice and comparable to Jupiter's red spot travels at a speed of 1,200 kilometers per hour. There is less turbulence and fewer storms on Neptune than Jupiter requiring less energy needed to maintain the high wind speeds. The dark spot on Neptune unlike Jupiter's red spot is not permanent.

Weather systems are important because they can contribute to environmental changes which in turn influence the seasons and consequently life.

Liquid Water

Microbial life on Earth is more robust than we believed it to be 25 years ago surviving in extreme environments such as freezing temperatures underneath and within Antarctic sea ice, in boiling ocean vents, rocks deep within the Earth's crust and in acidic rivers. The possibility for life elsewhere now centers on the search for water whether it is past or present.

Mars is once again at the forefront of our search for life. Billions of years ago there was a great deal of water on the surface with huge floods carving massive canyons. Recent evidence obtained by the Mars Global Surveyor spacecraft indicate that there could be transient streams that have recently burst out of the canyon walls from underground carrying rock and debris downstream into a basin (Fig. 9). It is assumed that the water erupted where there was sufficient heat from volcanic activity to have kept it liquid, rather than frozen, beneath the surface.

Water is known to currently exist on Mars both in the atmosphere and frozen in the polar caps. The north cap is composed of both water ice and dry ice (solid carbon dioxide) while the south cap is all dry ice. If the evidence for liquid water on the surface is verified it will have a tremendous impact on our search for life and its ready access will greatly simplify the investigations.

Mars is not the only place to look for water. Jupiter's moon Europa has become a surprising candidate. Five times further from the Sun than Earth and with sunlight only 4% as bright, the Jovian system would seem to be too cold to harbor a liquid ocean. However Jupiter is so massive that the same tidal forces that flex the surface of Io and result in active volcanoes also flex the surface of Europa but not as strongly. We know that Europa is covered with water ice and we now believe that tidal heating melts the ice beneath the moon's crust forming a liquid ocean.

Close-up images of the surface reveal cracks and ridges and places where the surface has been broken as if from a warm upwelling of a substance with the reddish-brown color characteristic of Epson salts indicating that a salty material is seeping from below. There are areas where the highly patterned, regular surface, appears to have broken apart into ice flows and floated apart before the material in between refroze (Fig. 10) similar to the ice flows seen in spring in the Arctic. This mobile surface suggests a subsurface fluid. A measured magnetic field also strongly supports the idea of a conducting liquid beneath the icy crust, most likely a salty ocean.

Conclusion

The first four decades of space exploration have brought us a wealth of information and understanding about the solar system. Future missions will probe more deeply into the origins and evolution of these worlds by physically examining the material. We will land laboratories on these bodies similar to the Viking and Mars Pathfinder missions (Fig. 11) to analyze samples that are critical to our understanding of the fundamental processes that have shaped these worlds and the role they have played in the origin and evolution of life.

In parallel to the detailed exploration of our solar system is the search for other planetary systems. Ground-based observatories such as the Keck Observatory in Hawaii have already detected such planets. Space-based telescopes such as the Hubble Space Telescope have discovered nebula nurseries that are in the early stages of planetary formation.

Just as the past millennium has completely revolutionized our view of the solar system there is every reason to believe that our view of the universe during the next millennium will bring discoveries that are even more exciting.

FIGURE CAPTIONS

Fig. 1 Three-dimensional, computer-generated view of the surface of Venus. Gula is three kilometers (1.8 miles) in height and Sif Mons (on left) has a diameter of 300 kilometers (186 miles) and a height of two kilometers (1.2 miles). The simulated color images taken by the Magellan spacecraft has a vertical exaggeration of 22.5 times.
[PIA00200]

Fig. 2 Active volcanic eruption on Jupiter's moon Io imaged by the Galileo spacecraft.
[OIA02550]

Fig. 3 Voyager 1 looking back on Saturn and its rings.
[PIA01969]

Fig. 4 Evolution of Comet Shoemaker-Levy 9 Fragment G impact site on Jupiter imaged by the Hubble Space Telescope.
[PIA01263]

Fig. 5 False color image of layers of haze covering Saturn's moon Titan.
[PIA01533]

Fig. 6 First time images of Titan's surface with prominent bright area 4,000 kilometers (2,500 miles) across, about the size of the continent of Australia.
[PIA01465]

Fig. 7 Two of Jupiter's moons, Io (left) and Europa, shown by Voyager 1 in front of Jupiter's Great Red Spot.
[PIA00144]

Fig. 8 Neptune's Great Dark Spot storm system accompanied by bright, white clouds and another storm further south.
[PIA01142]

Fig. 9 High resolution view from the Mars Global Surveyor spacecraft showing channels and associated aprons of debris that are interpreted to have formed by groundwater seepage, surface runoff, and debris flow.
[PIA01035]

Fig. 10 Ice pack on Jupiter's moon Europa.
[PIA01127]

Fig. 11 A 360-degree panorama imaged by the Mars Pathfinder spacecraft. [PIA01466]